GRID FEEDING Z-SOURCE INVERTER FOR SOLAR PHOTOVOLTAIC SYSTEM

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***Abstract*-The demand for renewable resource is increasing day-by-day. Hence the techniques using the solar energy are created in advancement for the requirement. High efficiency and operating life of grid feeding solar photovoltaic (PV) inverters are demanded. Current source inverter (CSI) offers higher reliability than the voltage source based solar inverter. But in order to address the limitations of the CSI model, a Z-source inverter is proposed. High earth leakage current is being fed into the grid in CSI technique. In this paper we have proposed a method of minimizing the leakage current and the Total Harmonic Distortion(THD) using Z-Source Inverter.**

Keywords—Z-source Inverter component; grid feeding system; solar photovoltaic(PV).

I. INTRODUCTION

Renewable energy sources are of great interest for DC systems. The DC's are recently investigated to feed power to the grid. Nonlinear load connected to the grid deteriorate the power quality of the grid and causes various power quality problem. Among these power quality problems harmonics and unbalance are of main concern. The multilevel inverter is used to feed power to the grid with minimum THD and unbalance. Instead of utilizing the traditional inverters for boosting the DC voltage, Z source inverter can be used. The Z-source inverter, overcomes the following drawbacks of traditional converter.

Problems found in traditional converters are as follows

- They operate in either boost mode (CSC) or buck mode (VSC), not in buck-boost mode.
- Misdating of switches may cause shoot through in a VSC or may cause an open inductor circuit in CSC, which can destroy the switches.
- Dead time for VSC and overlap time for CSC can cause waveform distortion.
- The power circuit topology of VSC and CSC are not interchanged, that is VSC main circuit cannot be used for CSC or vice-versa.

The Z-source inverter has unique shoot through state which is responsible for providing buck or boost feature to the inverter. No dead time is required for safe commutation in ZSI. Whenever renewable energy source is used as a DC input, MPPT is necessary to provide maximum power at any environmental conditions. The PV characteristics have complex relationship with the irradiance and with the temperature.

The PV characteristics get affected with the change in irradiance and temperature. The Perturb and Observe (P&O) method is used to track the maximum power at given environmental conditions. Here, MPPT is also used to provide shoot through state in ZSI. Synchronization of grid is an important issue and thus Phase locked loop (PLL) has been used. PLL generates the fundamental output voltage which is then applied to the closed loop controller, thus the grid frequency is synchronized with the inverter frequency. Power feed to the grid must be at unity power factor and with less distortion. For this a closed loop controller is designed which incorporates the action of voltage controller and current controller. The switching of the inverter is dependent on the grid voltage and grid current whereas the shoot through state for providing the boost is carried out using MPPT. The parameter design of Z-source inverter plays an important role for providing maximum boost to the inverter. Section II explains Z-Source inverter. Section III explains the control strategy and Section IV presents the simulation. Section V summarises the result.

II. Z-SOURCE INVERTER

The Z-source inverter (ZSI) topology used in power conversion has unique features that can overcome the limitations of VSI and CSI. Fig 1 shows the structure of Z-source converter. Although DC/AC conversion is the most common application of the Z-source topology, it can also be applied for power conversions involving AC/DC and AC/ AC applications. The X shape impedance is the Z-source impedance network comprises of two split inductors and two capacitors to provide a coupling between the DC source and the inverter bridge.

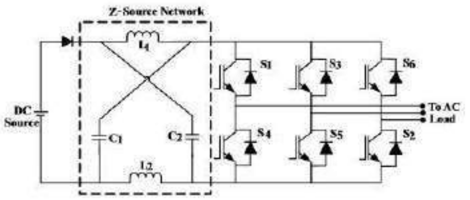

Fig.1: Three-phase ZSI

The Z-source inverter (ZSI) has the unique buck-boost capability which provides an output voltage range from zero to infinity regardless of the input voltage. This output voltage range is obtained with an unique switching state, termed as "shoot-through" state. This state is obtained when both upper and lower switches of the same phase leg are turned on. In a conventional VSI switching pattern, the permissible switching states are eight. The six switching states where the load sees the input voltage are called the "active" states and the remaining two states where either all the upper or all the lower switches are on and the load sees zero voltage are called the "zero" states. The output voltage of inverter can be given as

$$V_t = V sin\theta \tag{1}$$

$$M = \frac{V}{V_{dc}} \tag{2}$$

$$D = \frac{1 - M sin\theta}{2 - M sin\theta} \tag{3}$$

Where M is the modulation index and ϴ the output voltage angle.

The Z-source inverter has two operating modes: Shoot through mode and Non shoot through mode. Fig 2 shows the equivalent circuit of ZSI at non shoot through mode. In this mode the inverter is in one of the six active states. The diode gets forward biased and load is supplied.

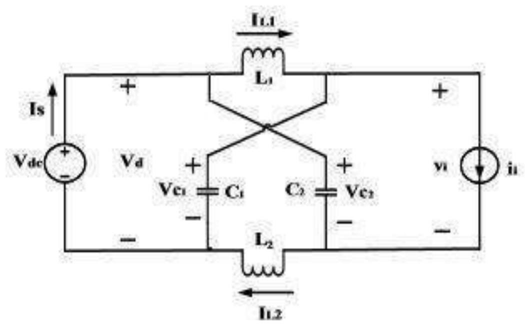

Fig.2: Non-Shoot through Mode

Assume the Z-source inductors (L_1& L_2) & capacitors (C_1& C_2) respectively. From the equivalent circuit, we have because of symmetry.

$$V_{L1} = V_{L2} = V_L, \qquad V_{C1} = V_{C2} = V_C \tag{4}$$

When the ZSC is in the non-shoot through state for a period T_1. From Fig. 2, the inductor voltage and output voltage of the inverter are expressed as

$$V_L = V_{dc} - V_C, \quad V_i = V_C - V_L = 2V_C - V_{dc} \tag{5}$$

When two switches of any three phase legs are made on at the same time, the circuit enters the shoot through state, where sum of the two capacitors voltage is greater than the dc source voltage($V_{C1}+V_{c2}>V_{dc}$) the capacitors charge the inductors with the diode being in reverse biased condition. The voltages across the inductors are

$$V_{L1} = V_{C1} = V_{L2} = V_{c2} \tag{6}$$

The average voltage of an inductor over a complete period T is zero in steady state, the capacitor voltage can be derived as

$$V_C = \frac{T_1}{T_1 - T_{sh}} V_{dc} = \frac{1 - D}{1 - 2D} V_{dc} \tag{7}$$

Where $T = T_1 + T_{sh}$ is the switching period &

$D = T_{sh}/T$ is the shoot through time duty ratio.

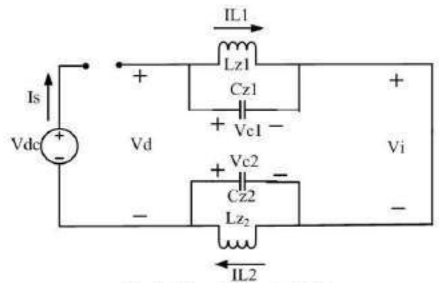

Fig.3: Shoot Through Mode

V_C is the steady state (dc) value of capacitor voltage & V_{dc} the steady state value of the input voltage. Similarly output voltage V_i can be derived as

$$\boldsymbol{V_i = \frac{1 - D}{1 - 2D} V_{dc}} \tag{8}$$

As equation (7) and (8) has equal right hand side hence left hand side should be same. Hence

$$V_i = V_c \tag{9}$$

$$D = 1 - M \tag{10}$$

Where M is the modulation index, the boost factor B can also be derived as

$$B = \frac{1}{1 - 2D} \geq 1 \tag{11}$$

From equation (7) & (8) boost factor can be given as

$$B = \frac{1}{2M - 1} \tag{12}$$

In Z source network values of inductor and capacitor play a very important role. The voltage boost required depends on shoot through time period but it is also dependent on the rating of capacitor and inductor, if values of Z source network is not calculated properly then the required amount of boost will not be obtained at output side and causes adverse effects in terms of ripples. The sinusoidal pulse width modulation techniques which are carrier based, like IPD, APOD, POD and phase shift pulse width modulation can be used for Z-source inverter. To provide shoot through state in the ZSI different boosting technique is studied. The different boosting techniques are the simple boost control, the maximum boost control, the 3rd harmonic injected constant boost control and the 3rd harmonic injected maximum boost control method. For providing shoot through state in the ZSI simple boost control technique is used with phase shift PWM as shown in Fig 4.

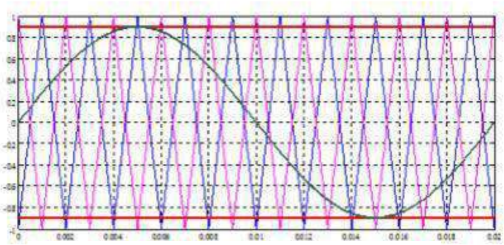

Fig.4: Simple Boost control of ZSI

As shown in Fig. 4 the Sinusoidal PWM (SPWM) is generated by comparing carrier triangular wave with reference sine wave. For generation of shoot through pulses, the carrier wave is compared with two complementary DC reference levels. For realization of shoot through duty ratio (D), two envelopes with constant magnitude are employed. The first envelope is equal to the peak value of the sinusoidal reference voltages while the other one is the negative of the first one. Whenever the triangular carrier wave is higher than or lower than the positive and negative envelope the inverter will operate in shoot-through mode whereas it operates as traditional inverter.

III. CONTROL STRATEGY

To feed good quality of power to the grid the control strategy is carried out as shown in following Fig 5.

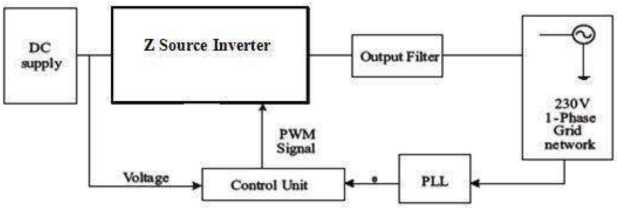

Fig.5: Control Strategy of ZSI

The circuit diagram for Z-Source based grid connected system is shown in Fig 5. Here PV module is used as a DC input. As we know that PV voltage is not much sufficient to feed power to the grid, the Z-source impedance network is connected at the output of PV. A three level cascaded H-bridge inverter is used to feed AC power to the grid. The Z-Source inverter is connected to the grid through the interface inductor. The interface inductor is used to reduce the harmonics in the grid current.

For synchronization of inverter frequency with grid frequency, a closed loop controller is designed, which is also responsible for firing switches of inverter. In this control unit the phase locked loop (PLL) block is utilized to synchronize inverter frequency with the grid frequency. The I is then multiplied with ref fundamental grid voltage and the resultant obtained is then compared with the grid voltage. The sine wave obtained from the control unit is then compared with the triangular carrier wave to obtain the pulses. For providing boost to the inverter shoot through state is necessary, this shoot through state is generated by using maximum power point tracking (MPPT) method. The Perturb and observe (P&O) method of maximum power point tracking is used in this work. The Perturb and observe method, will track the maximum power at any environmental condition and gives the maximum power at the output of PV. Here the Perturb and observe method is also used to provide shoot through state for providing the maximum boost to the inverter.

Perturb & Observe (P&O) is the simplest method of tracking MPP. The time complexity of this algorithm is very less. Only voltage sensor is utilized to sense the PV array voltage and so the cost of implementation is less and hence easy to implement. It keeps on perturbing in both the directions. When this happens the algorithm reaches the MPP and we can set an appropriate error limit. In this method the controller adjusts the voltage in lesser amounts from the array and measures power; if the power continues to increase then further adjustments are carried out in that direction and is continued till there is not an increase in power, which eventually leads to maximum point. This is called a 'Perturb and Observe' method.

IV. CONVENTIONAL MODEL

The conventional CSI is shown in Fig. 6. String of PV modules is connected across the input dc capacitors. The dc-link is realized by two capacitors, connected in series. Midpoint of these capacitors is connected to the neutral of the grid. DC-link inductors L_{dc1} and L_{dc2} are wound on the same core and therefore have a high value of mutual coupling. To generate ac current waveforms from the dc current, eight semiconductor switching devices are used. Each device has unidirectional current flow capability and can block the reverse voltage.

Either a diode connected in series with IGBT or reverse blocking (RB) IGBTs can be used to realize these switches.

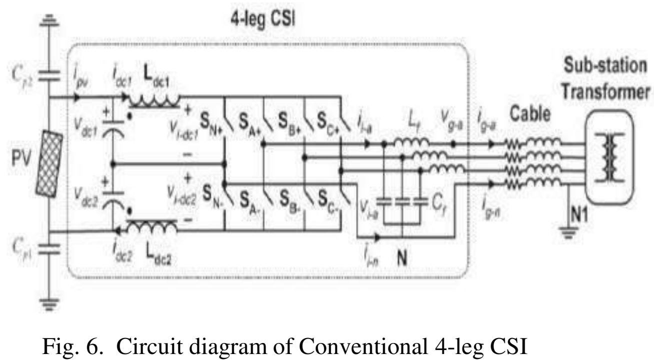

Fig. 6. Circuit diagram of Conventional 4-leg CSI

Output of three phases is connected to the grid through capacitor–inductor (C–L) filter and that of the fourth leg is connected to the neutral of the system as shown in Fig. 6.

A scaled-down laboratory prototype is developed for experimental verification of the conventional converter. TMS320F28335 controller is used to implement the control laws derived for the proposed topology. IXYS made RB-IGBTs(IXRH40N120)are used as semiconductor switches. Interrupt-based timer modules of the controller are used to generate space vector PWM signals. To interface the controller with IGBTs, Semikron made Skyper 32PRO drivers are used. Various parameters of the prototype are given in Table I. Agilent Technologies made solar PV emulator (E4360) is used as dc input source. DC-link voltages and currents are shown in Fig. 7. DC-link voltages v_{dc1} and v_{dc2} are 149 V and 153 V, respectively. DC-link currents i_{dc1} and i_{dc2} are 6.28 A and 6.29 A, respectively. This confirms that both dc-link currents are almost equal. Fig. 8 shows the phase-a grid voltage v_{g-a}, inverter PWM current $i_{i-a,}$ and grid current i_{g-a}. Grid current is in phase with grid voltage, and power factor is found to be 0.99. Total harmonic distortion (THD) of the grid voltage and currents supplied are 1.7% and 5.9%, respectively. Unity power factor operation and low THD confirm the usability of the conventional circuit as grid feeding solar inverter. Fig. 9 shows the phase-a grid voltage and neutral current. RMS value of the neutral current is 159 mA. Average component of this current leads to unbalance in dc-link capacitor voltages. Due to small value of this current, both capacitor voltages are expected to be almost equal. This is in agreement to the observed values of capacitor voltages V_{dc1} = 149V and V_{dc2} = 153V.However, if significant unbalance in capacitor voltages is observed, a zero sequence based controller can be designed . The common mode voltage (between ground and −ve dc-link) in the conventional scheme is compared with that in conventional three-phase PWM CSI. Fig. 8. shows experimentally obtained common mode voltage in the conventional CSI. Absence of switching frequency components in the proposed scheme confirms the immunity of the circuit to suppress the earth leakage currents.

TABLE-I

PARAMETERS FOR SIMULATION AND EXPERIMENTAL PROTOTYPE

Parameter	Value	Value (in p.u.**)
Grid phase voltage, V_{g-a}	220V	0.92
AC filter inductor, L_f	1.8mH	6.6m
AC filter capacitor, C_f	3.3μF	89m
Common mode inductance of DC choke, L_{dc-cm}	400mH	2.8
Differential mode inductance of DC choke, L_{dc-dm}	1.2mH	8.4m
DC-link capacitors, C_{dc}	50μF	0.71
Reference dc-link voltage	300V	1
Sampling Frequency	7.5kHz	-

$^{**}P_{base}$=2kW, V_{base}^{DC}=300V, V_{base}^{AC}=415V & F_{base}=50Hz

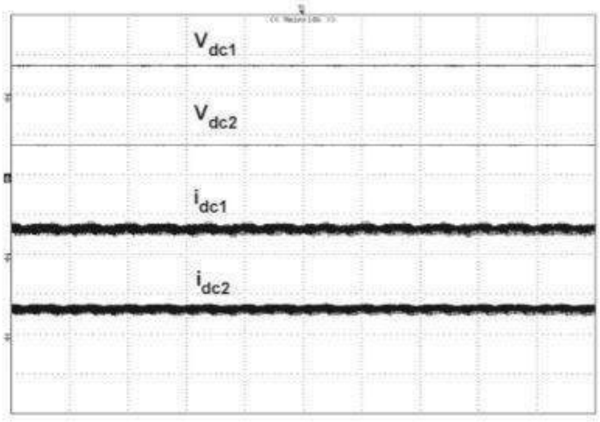

Fig. 7. Experimental results: dc capacitor voltages v_{dc1} and v_{dc2} (200 V/div) and dc inductor currents i_{dc1} and i_{dc2} (10 A/div). X-axis: time (10 ms/div).

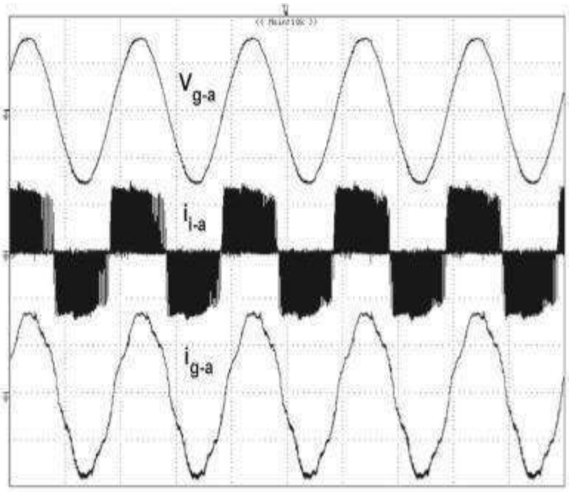

Fig. 8.Experimental results: ac phase-a voltage v_{g-a} (200 V/div), inverter PWM current i_{i-a} (5 A/div), and grid current i_{g-a} (2 A/div). X-axis: time (10 ms/div).

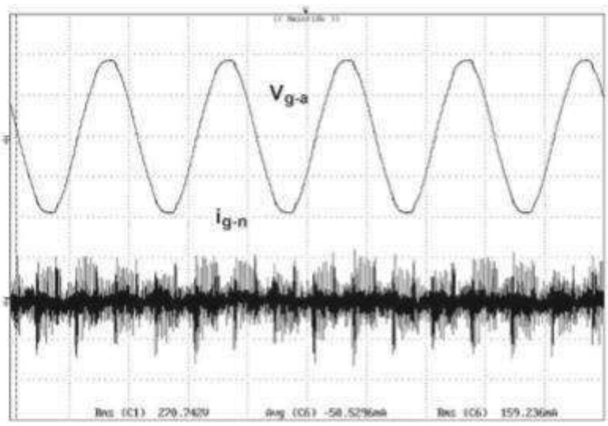

Fig. 9. Experimental results of the conventional scheme: phase-a voltage v_{g-a} (200 V/div) and neutral current i_{g-n} (0.5 A/div). X-axis: time (10 ms/div).

V. PROPOSED SYSTEM

The conventional method of the CSI has disadvantages of having the leakage current to be of high order. In order to suppress them to a still minimal level and boost the value to a much higher ratio, the Z-source inverter connection is made in the form of block diagram using Fig. 10.

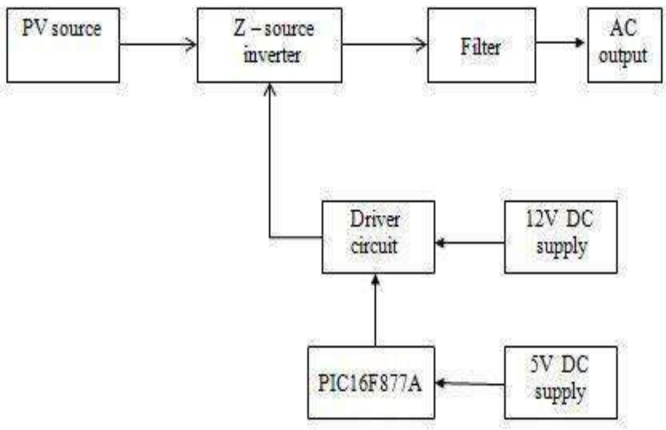

Fig.10: Block diagram of Proposed ZSI

Fig. 10.represents the step-by-step method of operating the PV system and feeding the ZSI by the use of DC voltage it acquires. This is fed to the harmonic clearance system consisting of the active LC filters which reduce the THD to a desired value. The less-ripple obtained circuit is fed to the grid. The circuit shown in Fig. 11.represents the general circuit of the ZSI connected to the grid. The circuit consists of a solar PV solar panel, a diode(D) , an IGBT switch , Z-source network , inverter unit , LC filters and transmission cables

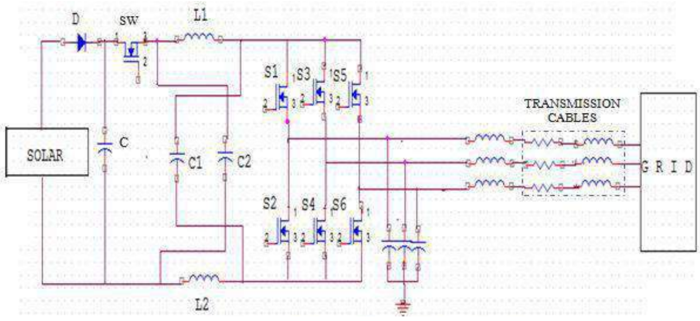

Fig.11: Circuit diagram of Proposed ZSI

feeding the grid network. PV acts as the source to the entire network. The diode present next to it , prevents the flow of reflective signals from the system to the source. The switch enables the boosting operation and prevents system from short circuiting during the shoot-through state. The L_1,L_2,C_1&C_2 forms the Z-source network. The inverter unit converts DC-AC.The operation of the proposed system starts with the PV panel supplying the base voltage to initiate the process by tracking the MPP. The supply is fed to the diode D and to the switch (SW), and through this the inductance and capacitance of the Z-source network gets charged. At this junction, the normal inverter operation takes place in the system. Depending on the reference voltage and the current, the gate pulses are given to the inverter unit and the shoot-through state occurs. During this state, the switch (SW) opens automatically by the controller operation and prevents the system from short circuiting.

At the shoot-through state, the inductance (L1,L2) and the capacitance (C1,C2), which is already charged gets charged again and as a result , the voltage in the output phase gets boosted. The boosted output is passed on to the LC filter circuit and fed to the grid which minimizes the THD level to less than 5%.Thus the supply voltage is boost and the harmonics are reduced and the boosted less harmonic power is fed to the grid using the ZSI as proposed in this paper.

VI. SIMULATION RESULTS

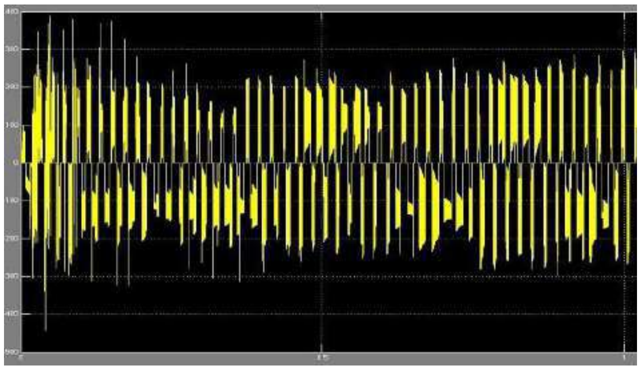

Fig. 12. Simulation of the boosted output waveform using ZSI

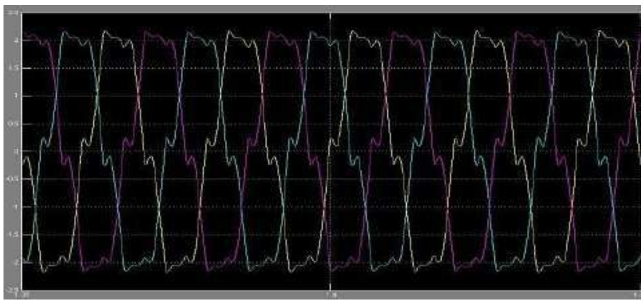

Fig. 13. Simulation of output current waveform with distortion

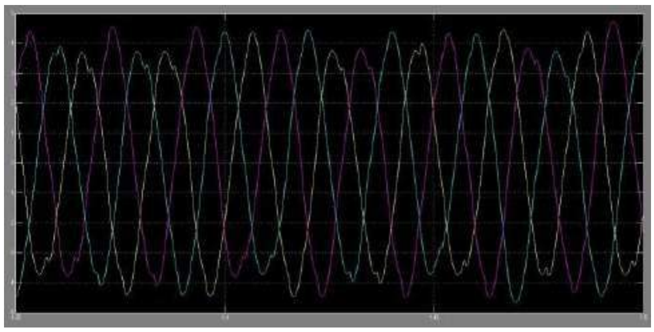

Fig. 14. Simulation of the output current waveform without distortion

In order to verify the proposed scheme, a Z-source based grid feeding inverter is simulated on MATLAB Simulink utilizing the parameters given in Table II.

TABLE II
PARAMETERS FOR PROPOSED MODEL SIMULATION

Parameters	Value
Grid phase voltage	440 V
Inductance of L_1,L_2	1e-3 H
Capacitance of C_1,C_2	1e-6 F
Reference voltage	400 V
Reference current	1.8 A
Pulse Width of Gate Driver	70%

VI. CONCLUSION

This paper recommends the use of Z-source based solar inverters to reduce the leakage current as compared to conventional current source based inverters. It is shown that conventional CSI injects much higher earth leakage current and has THD of higher value. To address this limitation, ZSI can be used and this will boost the voltage to a value that can be fed to the grid and the distortion is reduced to around 5% or less. Detailed simulation studies are carried out to predict the performance of the system and the simulation results shows the outputs of both the condition of the output current with and without distortion.

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